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(2017)

DOI (TUprints): https://doi.org/10.25534/tuprints-00014287

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Publication type: Article

Division: 16 Department of Mechanical Engineering

Original source: https://tuprints.ulb.tu-darmstadt.de/14287

Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 9 (2017) 25 – 32

Procedia MANUFACTURING

7th Conference on Learning Factories, CLF 2017

Utility-based configuration of learning factories using a multidimensional, multiple-choice knapsack problem

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Abstract

The paper presents a structural approach to configure the technical system of a learning factory by considering learning targets and maximizing the utility. Local scope conditions and intended competencies are used to operationalize requirements. The composition of the module-based technical system can be optimized by maximizing its overall utility. Therefore, an exact and efficient optimization algorithm is developed solving a multidimensional multiple-choice knapsack problem combined with a two-dimensional bin packing problem. Restrictions are the available budget and the useable area of the learning factory. As a result, the configured technical system enables optimal target orientation of the learning factory. This procedure is finally applied on the Process Learning Factory CiP.

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Peer review under responsibility of the scientific committee of the 7th Conference on Learning Factories

Keywords: learning factory, technical system, competency development

1. Introduction

Employee's competencies are the key resources of an enterprise to quickly adapt to ever changing conditions [1]. In this context competency development at all levels is needed for those adaption processes [2]. One promising approach for effective development of competencies is the learning factory concept. In recent years more and more learning factories were built up in industry and academia [3]. In particular, with respect to the specific design of the (socio-) technical system of a learning factory (also short: LF), systematic approaches to a competency-oriented design are lacking. Based on the LF design models and methods according to [4,5], this paper addresses the configuration of (socio-) technical systems in LF.

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doi:10.1016/j.promfg.2017.04.017

2. Learning factory design

Within the CIRP CWG (Collaborative Working Group) on Learning Factories for future-oriented research and education numerous explicit and implicit definitions of the term "learning factories" were identified, analyzed, and compared, in order to strive for a common understanding. Dominant key features of LF were extracted, resulting in a common understanding of the LF concept in the narrow and in the broader sense, see also Figure 1. The definitions are summarized in the CIRP Encyclopedia [6]:

"A Learning Factory in a narrow sense is a learning environment specified by **processes** that are *authentic*, *include multiple stations*, and comprise *technical* as well as *organizational* aspects, a **setting** that is *changeable* and resembles a *real value chain*, a *physical* **product** being manufactured, and a **didactical concept** that comprises *formal, informal and non-formal learning*, enabled by *own actions of the trainees* in an *on-site learning* approach. Depending on the **purpose** of the Learning Factory, learning takes place through *teaching*, *training* and/or *research*. Consequently, learning outcomes may be *competency development* and/or *innovation*. An operating model ensuring the sustained operation of the Learning Factory is desirable. In a broader sense, learning environments meeting the definition above but with a setting that resembles a *virtual* instead of a *physical value chain*, or a *service* product instead of a *physical* product, or a didactical concept based on *remote learning* instead of *on-site learning* can also be considered as Learning Factories."

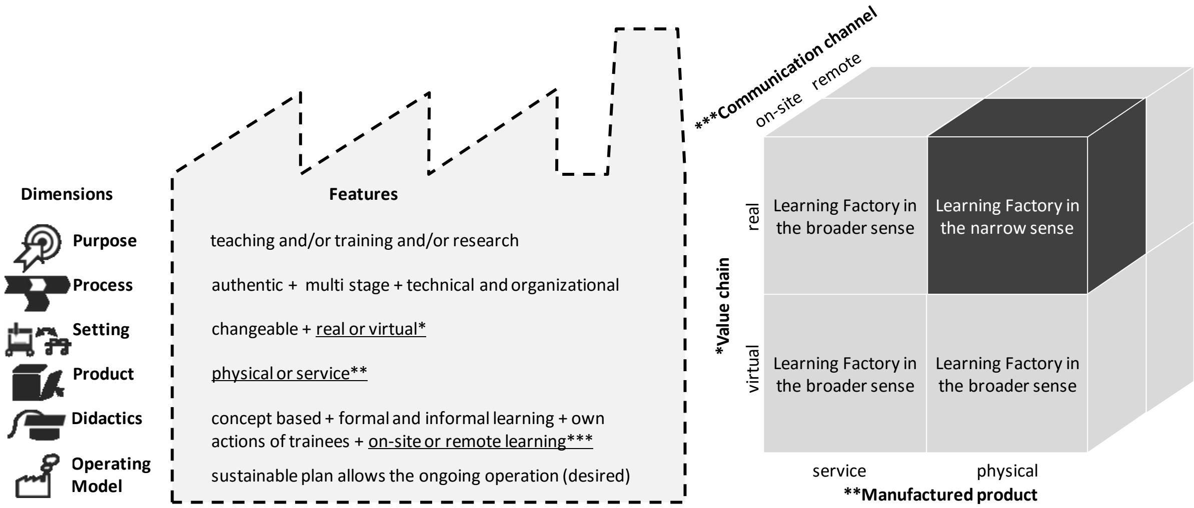

Figure 1: LF key characteristics and distinction between LF in the narrow (dark cube) and in the broader sense (all light fields) [3]

The complex system LF comprises many interconnected concepts. In order to structure the LF concept in general a morphological description model is developed with in total 59 characteristics in seven dimensions (s. Figure 1, the dimension "metrics" is excluded in this paper) [5]. Furthermore three conceptual design levels of LF are defined to structure the understanding for different design objects [4], see also Figure 2. At each level, the design process can be intersected in a first didactic transformation, dealing with the question what content should be selected, and a second didactic transformation, dealing with questions of how this selected content can be transported [4,7]. This paper addresses the second transformation on macro level (first design level), namely the competency-oriented design or configuration of the socio-technical infrastructure of a LF. The presented approach supports the LF design step by using a structured, algorithm-based method to maximize the overall utility of the technical system of the LF using general requirements, intended competencies, and didactical infrastructure.

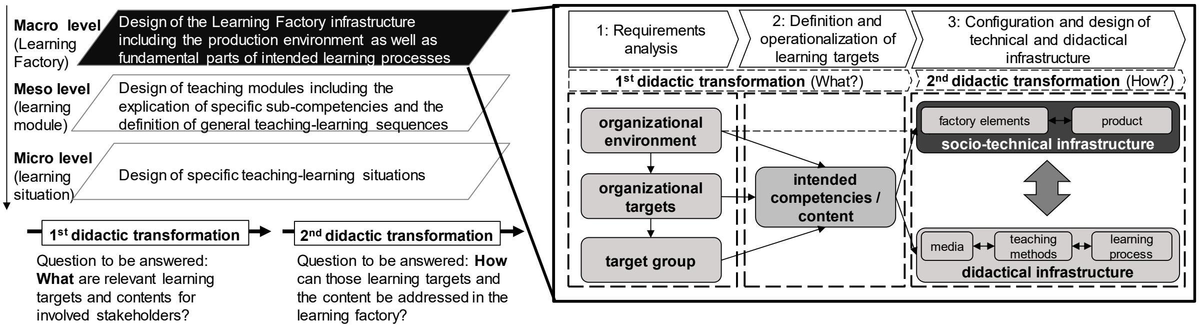

Figure 2: (a) Conceptual LF design levels [4], (b) Overview on the elements of the first and second didactic transformation on macro level [4,7].

3. Configuration of the technical system of learning factories

In this section, a method for the requirement-based configuration of the (socio-)technical LF system is given. The method is embedded into the holistic competency-oriented approach of [4]. In this method the technical system is derived from a predefined product to be produced in the LF. Therefore, different factory ***modules*** (e.g. assembly, manufacturing) and ***sub-modules*** (e.g. sawing, milling) are defined along the value stream. For each sub-module LF items are selected and combined (***elements***, see Figure 3) in a way that they may work in a LF setup. Those elements are evaluated concerning their utility for the overall LF concept based on predefined requirements. In a last step the whole technical system is configured using a mathematical optimization maximizing the utility considering physical and monetary constraints. The approach is conducted in five steps:

1) Definition of requirements,
2) Modularization of the technical system,
3) Generation of technical elements,
4) Assessment of utility,
5) Optimization.

Step 2) Modularization of technical system

● = strong
○ = medium
▽ = weak

Step 1) Definition of requirements | **Step 3) Generation of technical elements** | **Step 4) Assessment of utility**

Customer relevance score	Requirement class	Requirement \ Element	…	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	…
		Main-module	…	Manufacturing																…
		Sub-module	…	Sawing				CNC Turning				Milling				Cleaning				…
		Element	…	Low budget band saw	High-end band saw	Low budget circular saw	High-end circular saw	2 x low-budget turning machine	2 x autom. turning machine	High-end turning machine center	High-end + compact machine	High-end + 4x compact machines	high-end machining center	2 x Universal machining center	4x compact machining centers	Manual parts cleaner	Half automatic parts cleaner 1	Fully automatic parts cleaner	Compact laser cleaning station	…
2	a) Competency-oriented learning goals	Requirement 1.1			●		○	●	●		●		●		●	○	○	▽	●	
7		Requirement 1.2		▽	○		○	▽	○	▽	○	▽	○	▽	○		○	▽		
4		Requirement 1.3			▽		○	○	○		▽	○	○		●	▽		●	○	
6		Requirement 1.4		▽	○	●		●	○	○		●	○		○	○	○		▽	
6	b) General and learning factory-oriented framework	Requirement 2.1		▽	○	○	○	○			○	●	●	○		●	●	▽	▽	
6		Requirement 2.2		●	●			●	▽	●		●	▽	●	●	▽	▽	○		
6		Requirement 2.3			○	○	○	▽		▽	○	○	●	○	○	▽	▽		○	
5		…		▽	○	●		●	○	●	●		○	●	●	▽		▽	○	
…	⋮	…																		
…		…																		
Technical feasibility			…	8	8	7	8	7	7	7	8	7	7	7	8	8	8	6	9	…
Utility score			…	111	204	202	143	241	117	182	182	221	240	254	223	107	129	145	134	…

Figure 3: Requirement-based utility assessment of technical elements of the LF

The methods underlying restrictions are: (R1) The method addresses LF in the narrow sense, see [3]. (R2) The LF focus is on education and training for lean production. (R3) The LF system maps the production of one real product and its variants. (R4) Relevant information, goals and requirements are available. (R5) The method is applied by an interdisciplinary project team to consider expectations of stakeholders.

Step 1) Definition of requirements: Requirements on LF are varying strongly, which can be seen in the large amount of different LF, see e.g. [3,8–10]. In course of the individual requirements definition the following classes of requirements are taken into account: a) requirements coming from the competency-oriented learning targets, b) general and LF framework requirements (based on the morphology), c) organizational, learning system-related requirements (based on company goals), d) requirements coming from target working system and target group, e) additional related requirements. The requirements are operationalized in order to define assessment criteria. The subjective customer requirements and didactic goals are transformed into objective and target-oriented criteria for assessing technical elements on various factory levels. Figure 4 exemplarily shows a table for the operationalization of competency-oriented learning targets. Other requirement classes (b-e) are operationalized accordingly.

Class	Criteria	Factory Levels					
		Network	Factory	System	Segment	Cell	Station
a)	Competency 1	-	-	-	-	Work content inside a cell can be redistributed among stations	stations inside a cell mainly contain manual work.
a)	Competency 2	Deducted requirements of predefined intended competencies on the factory levels					
…	…						
a)	Competency n						

Figure 4: Operationalization of requirements

Subsequently, operationalized requirements are weighted in a pairwise comparison and normalized to a relevance score of 10 (most important). Operationalized requirements from all levels are used in the utility assessment (Step 4), additionally requirements at station and cell level are used for the generation of the technical elements (Step 3).

Step 2) Modularization of the technical system: As a next step, the technical system is divided into functional areas, called modules. Using bills of material and manufacturing processes [11] clearly defined factory modules are determined containing primary activities [12] as well as complementary support activities like logistics, IT, production planning and controlling. The defined modules should resemble a realistic environment [3]. For a more detailed description every module is separated into several sub-modules. For example, the module manufacturing contains sub-modules like sawing, milling, drilling. Dependencies between different modules and sub-modules must be considered.

Not every module is useful for realization. Hence a selection of the determined modules is performed considering feasibility (cost and time consumption) and suitability (impact on the factory goals). The disregarded (sub-) modules force the focus on other modules or can be substituted by bought-in parts as a realistic manufacturing environment. The finally selected sub-modules are the basis for the selection of technical elements to configure the system.

Step 3) Generation of technical elements: Each sub-module (e.g. milling) of the technical system is detailed with different elements (i.e. combinations of specific milling machines and equipment, see also Figure 3). An element is defined as a full solution set for a sub-module of the LF. Elements consist in most cases of a combination of items that allow operation at different maturity levels (e.g. wasteful / good practice scenario), i.e. the element is defined as a proper and full solution to fulfil the requirements (possibility to fulfil takt time, changeability of equipment, etc.). Elements are defined with a significant diversity in order to open up a broad solution space. The goal is not to select one machine out of a set of machines with the same functionality and similar specifics from different manufacturers, but to find the best solution out of a broad solution range. As a result, sub-modules consist of several independently selectable complete packages. Later in Step 5 exactly one element per considered sub-module is selected.

Step 4) Assessment of utility: Each element defined in Step 3 is evaluated with respect to all operationalized requirements. For this purpose, an adapted value benefit analysis is conducted. The analysis structures the assessment process by providing a standardized matrix (see Figure 3), composed of the two dimensions: a) the operationalized requirements as assessment criteria (vertically) and b) the modules, sub-modules and elements (horizontally). The evaluation is done by four rating grades on a cardinal scale: strong, medium, weak and no satisfaction. The result is recorded in a matrix by using symbols, instead of numbers, in order to mitigate an anchoring effect [13].
To approach the complexity of assessing technical elements by mostly non-technical requirements a discussion integrating different points of view is intended, thus experienced members of an interdisciplinary project team are integrated in the assessment. Thus, based on the predefined requirements the potential solution sets (elements) are evaluated in consensus inside the project team. Finally, the cardinal rating grades are matched with numerical values using the most common combination 9-3-1-0. For each element a total value of utility is calculated by multiplying the rating grade with the relevance score of the respective requirement. All values in a column are summed up to the quantitative utility of a single potential LF element. The utility score states how good an element (solution set) fulfills the requirements. Further information like specific properties of costs and physical dimensions are collected separately.

Step 5) Optimization: To gain the maximum overall utility of the technical LF system the combination of elements with the highest utility are chosen. Usually due to restrictions the mere selection of elements with the highest utility score in all sub-modules at the same time in the same factory is not suitable. Here, two restrictions are considered:

1. The overall costs must be lower than the given budget.
2. The overall floor space must be lower than the given floor space.

The LF configuration is modeled using a multidimensional multiple-choice knapsack problem (MMKP):

- A knapsack problem maximizes a target function that represents the overall utility of all chosen elements (1).
- Multidimensional knapsack problems have more than one restriction: In our case cost and space (2).
- For each restriction k the upper limit is C_k. In multiple-choice knapsack problems each element is part of a class, in this case: the sub-module. Only one element can be chosen from each sub-module (3).
- If the binary variable (x_{ij}) is 1, the j-th element in the sub-module i is chosen (4).
- There must be at least one feasible configuration: Hence the maximal resource consumption C^k should not be to low (5). Formally, the MMKP can be stated as: [14]

$$\text{Maximize} \quad Z = \sum_{i=1}^{I} \sum_{j=1}^{J} U_{ij} x_{ij} \tag{1}$$

$$\text{Subject to} \quad \sum_{i=1}^{I} \sum_{j=1}^{J} w_{ij,k} x_{ij} \le C^k \tag{2}$$

$$\sum_{j=1}^{J} x_{ij} = 1 \tag{3}$$

$$x_{ij} \in \{0,1\} \tag{4}$$

$$\sum_{i=1}^{I} \min_{1\le j\le J}\{w_{ij,k}\} \le C^k \le \sum_{i=1}^{I} \max_{1\le j\le J}\{w_{ij,k}\} \tag{5}$$

$$i \in \{1, \dots, I\}, j \in \{1, \dots, J\}, k \in \{1, \dots, K\}$$

where I is the number of sub-modules, J is the number of elements in each sub-module, U_{ij} is the utility of j^{th} element in sub-module i, $w_{ij,k}$ is its consumption of resource k.

To solve the MMKP an exact branch-and-bound-algorithm is developed. First, all elements are arranged in descending utility and indicated by a rank. The first node contains all elements with the highest utility. In most cases this solution is not feasible. Therefore (maximal) I new nodes are created. In each node one rank is raised by 1. To avoid redundancy, the same node can only be created once. To illustrate this procedure Figure 5 shows the decision tree for a MMKP with three sub-modules. Each sub-module contains three elements.

To find the exact solution not every possible node must be created. There are two principles that confine this procedure: the overall utility of a successor node cannot be higher – so, if a node is feasible, no more successor nodes must be created, because these nodes cannot represent the optimal solution. Moreover, if a feasible node has a lower overall utility than another feasible node, no more successor nodes must be created, too. The branch-and-bound-algorithm ends, when the last created node is examined. To test this algorithm, the calculated solutions are compared with an enumeration algorithm: In all cases within a Monte Carlo method the exact solution could be found.

Although the overall area of a configuration is lower than the useable area, there is no guaranty that the chosen elements can be packed in the LF. Therefore, a two-dimensional bin packing problem (BPP) exists within the MMKP. Figure 6 illustrates this situation. In both cases the sum of the objects' area required is lower than the restricting overall area, but in contrast to the suiting solution on the left the configuration on the right is not feasible due to fixed item dimensions. The difference between elements and items is essential: while elements are treated in the MMKP, the BPP handles items. Elements (may) contain several items.

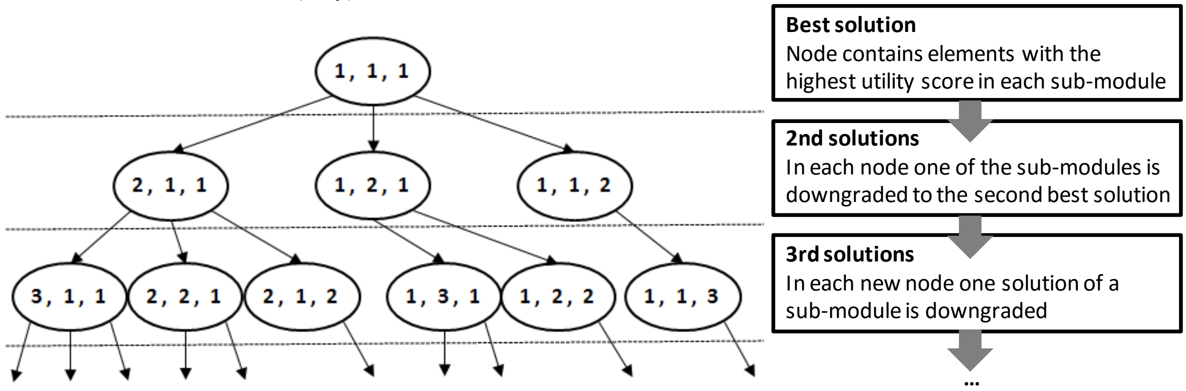

Figure 5: Decision tree of the branch-and-bound-algorithm

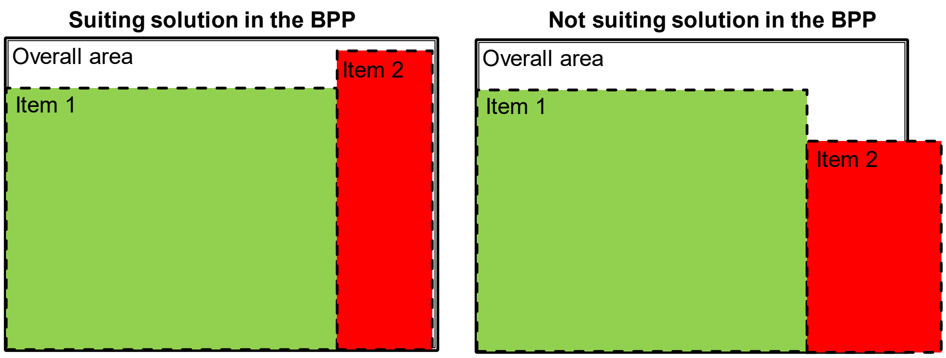

Figure 6: Exemplary BPP within the MMKP containing objects with the same required space

The BP-MMKP can be solved exactly with a feasible factor. The feasible factor is the ratio of the used area in the branch-and-bound-algorithm and the actual LF area (the product of length and width). A feasible factor less than 1 forces the branch-and-bound-algorithm to examine more nodes. To check the feasibility in a two-dimensional BPP several algorithms exist [15]. At first, the feasible factor equals 1 and the branch-and-bound-algorithm produces the first solution. If this solution is not feasible within the BPP or if the desired order of sub-modules in the LF cannot be achieved (considering value stream thinking), the feasible factor is reduced and the branch-and-bound-algorithm produces a new solution with less area. The reduction of the feasible factor should not be too large, because otherwise exact solutions may be skipped. Therefore, the amount of reduction should equal the smallest difference of area between two elements. In this case no solutions are skipped. The BP-MMKP algorithm ends with the first feasible solution.

4. Use Case: Reconfiguration of the technical system of the Process Learning Factory CiP

In this section for better understanding and validation purposes a use case is presented. The implementation of the method for Process Learning Factory CiP is elaborated. In this use case the method allows a revision of an existing technical LF system. The CiP complies the underlying restrictions R1-R5 defined in section 3.

First, customer requirements are analyzed and structured: For example the transfer of lean competencies (requirement class a) or a changeable and realistic manufacturing environment (requirement class d). In a next step these requirements are operationalized. In total 18 discrete and sound requirements are derived as assessment criteria.

For the value stream of the pneumatic cylinder adequate factory modules are identified. In regard to the purpose of the CiP *manufacturing*, *assembly*, *quality assurance*, *logistics* and *production planning and scheduling* are selected as modules. The selected sub-modules are sawing (S), milling, CNC turning (CNC) and cleaning (C) for *manufacturing*, pre assembly (PA), main assembly (A) and packaging (P) for *assembly*, measurement and functional test for *quality assurance* (QA), material reception, supply, and transport for *logistics* (L) and workplace and shop floor management (SFM) for the *production planning and scheduling*. All sub-modules are directly or indirectly involved in the value creation of the product.

For each sub-module five technical solutions (elements) are created. As mentioned earlier each element must be able to display a minimum of two different maturity states that may vary the environment regarding dimensions of interest, e.g. layout, work processes, or product specifications, see also [4]. The manufacturing elements are represented through small and high-end machining centers or combinations of both. The assembly is deduced from the product and expressed by different combinations of work places and tools. Logistics are represented by elements ranging from static shelves to flow rack and worker self-supply to automated milk run robots. Quality assurance is determined by manual up to automatic solutions. The elements of the shop floor management are composed of flipcharts, whiteboards, and interactive smart boards. Sub-modules may also be substituted by bought-in parts or may be neglected. Therefore, these sub-modules contain an empty element with no utility, no costs and no area.

In the presented case study, elements with a broad application range mostly gain significant higher utility than other elements of the sub-module. However, these elements often also consume the highest budget and occupy the most shop floor space. In the manufacturing module, the combination of small and high-end machining centers shows best results. Ergonomic optimized work places with sensor-driven electrical tools dominate the assembly. Flow racks and manual milk run carts match best with the requirements for the logistics. The quality assurance prefers half-automated solutions due to more flexibility. Finally, the production planning and scheduling is best represented by a mix of interactive smart boards with analogue flipcharts and whiteboards. Exemplarily, the length and width of the LF are determined to 24 m and 17 m (408 sqm, high size scenario) and 18 m and 14 m (252 sqm, low size scenario). Because each element needs an access to an aisle, the lengths and widths are adjusted. Furthermore, for all machines additional lengths are added for maintenance on all sides and for handling on just one side. Furthermore, to enable a proper supply of material, the length of all machines and all workstations is enlarged. Assembly and transport costs for all factory elements are not included. Also there is one low budget (15,000 €) and a high budget scenario (1,900,000 €) considered. After applying the BP-MMKP-algorithm to the technical environment, the floor plans in Figure 7 are derived.

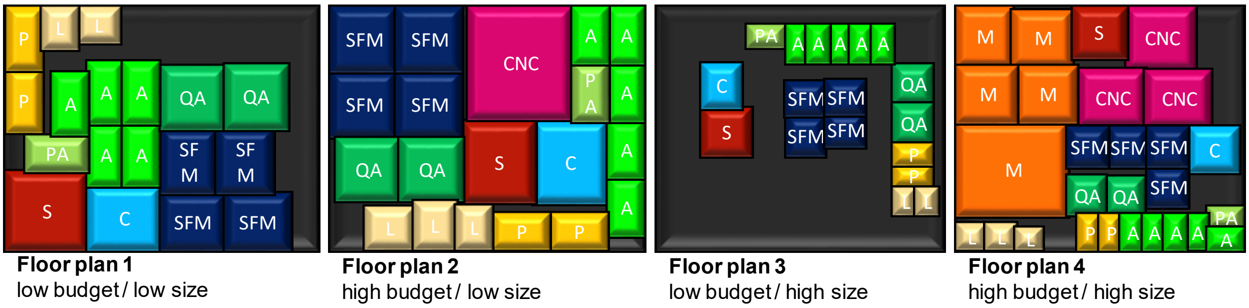

Figure 7: Floor plans for the configurations depending on available budget and size (size of floor plans (low/high) with modified scale)

Figure 8 (a) shows a 2x2-resource variation matrix. Four new configurations are calculated using the different sizes (27m x 23m and 18m x 14m) and budgets (1,900,000 € and 15,000 €). In this example, the optimized configurations using a lower budget are equal – so there is no need for more area in this case. A higher budget can be beneficial with less and more useable area. In comparison, the first solution above has overall costs of 974,650.71 € and an overall utility of 96.83% relative to the maximal reachable utility score. Furthermore, Figure 8 (b) represents the utility-costs-curve for the learning factory with the high size (27m x 23m). The marginal utility diminishes strongly with a higher budget.

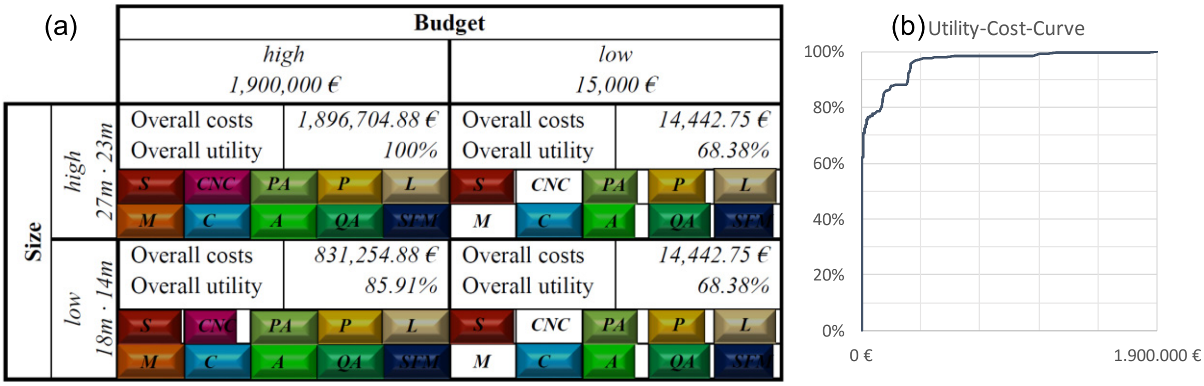

Figure 8: 2x2-resource consumption matrix of the configurations

5. Conclusion and Outlook

This paper provides a tool for the algorithm-based configuration of the technical system of a LF. To use the configuration tool for other products or other goals, the value added process, the customer requirements and the elements have to be adjusted. For more sub-modules or more elements, heuristics may be used when calculating time increases too much. Furthermore, the utility of each element can be measured more accurately if customer requirements are better understood. A modified version of this approach could also be applied to real factory planning.

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